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14. ABSTRACT
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Final Report

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ABSTRACT

Survivability of an aircraft in combat is achieved by not getting hit, or withstanding the effects of any suffered hits. To assess the latter aspect of survivability of a given military aircraft, live-fire tests are performed on its wings. However, these tests may fail to provide accurate and complete vulnerability assessments, because the static and quasi-static ground loading techniques they currently rely on do not replicate the loads encountered during flight, and do not account for changes in structural stiffness and mass after damage infliction. Furthermore, current live-fire tests do not address the damage-induced changes to the flight mechanics and aeroelastic stability of an aircraft; these changes can lead to the abortive impairment of the ability of this aircraft to accomplish its designated mission, or cause its premature failure. For these reasons, the present AFOSR Grant F49620-01-1-0052, entitled "Methodologies for Predicting and Testing the Effects of Combat Damage on Flight Envelopes," focuses on developing a numerical simulation technology for predicting the consequences of battle damage on the flight and flutter envelopes of fighters, assessing the impact of several contributors to aircraft survivability, and assisting in the development of new dynamic live-fire ground testing methodologies that may remedy the shortcomings of current static ground-testing techniques. The key components of this simulation technology are: (a) a three-field formulation of nonlinear coupled fluid-structure interaction problems in which the flow is modeled by the arbitrary Lagrangian-Eulerian form of either the Euler or Navier-Stokes equations, and the structure is represented by a detailed finite element model, (b) the coupled sensitivity analysis by the adjoint method of flight mechanics and flutter criteria with respect to damage parameters, and (c) fast computational kernels for enabling the investigation of "what-if" scenarios in a reasonable amount of CPU time. It is expected that the outcome of this research effort will promote realism not only in numerical simulations but also in live-fire tests, enhance design for survivability, and facilitate procurement decisions. This report focuses on the technical achievements made during the first two years of funding. At the end of the second year, the proposed research effort was transferred to Stanford University where the Principal Investigator had moved.

1 OVERVIEW OF THE STATED OBJECTIVES

It was proposed to conduct a three-year research effort focused on developing, validating, and exploiting a high-fidelity and high-performance numerical simulation technology for predicting the effects of combat damage on the flight and flutter envelopes of military aircraft. To this effect, it was proposed to build on previous achievements in CFD (Computational Fluid Dynamics)-based nonlinear computational aeroelasticity funded by AFOSR (Grant F49620-99-1-0007), and perform the following research tasks:

- *Advanced modeling and computational methodologies.* It was proposed to research and develop high-fidelity and high-performance methodologies for modeling and simulating the effect of damage on the aerodynamic performance, stability, control, and aeroelastic behavior of military aircraft. These include, among others, the concept of "phantom" elements for facilitating the introduction of damage in the computational fluid and structure models, fast methods for evaluating transient effects, and the sensitivity analysis by the adjoint method of flight mechanics and flutter criteria such as lift, drag, stability derivatives, and flutter speed with respect to various damage parameters including the size and location of a hole.
- *Dynamic live-fire ground-testing methodology.* Assisted by the developed simulation technology, it was also proposed to investigate a reconfigurable wing loading methodology based either on tethers or embedded piezoelectric actuators which replicates in-flight loading conditions, and allows the structure to properly react when damaged.
- *Validation.* Finally, it was proposed to collaborate with Dr. Greg Czarnecki and his team at the Wright-Patterson Air Force Base (AFB) to validate the proposed simulation technology, and assess the feasibility of the proposed dynamic loading methodology. It was also proposed to work with Dr. Mike Love at Lockheed-Martin Aeronautics to explore how the proposed modeling and simulation technology can help in reducing some of the test costs of the JSF (Joint Strike Fighter) program.

After one year of performance on this grant, the Flight Test Center at the Edwards Air Force Base requested an additional emphasis on *aeroelastic reduced-order models* to speed-up the prediction of the flutter envelopes of modern aircraft fighters. This request was accommodated in the form of an additional task (see Research Task 8 below).

2 SUMMARY OF THE PROPOSED RESEARCH EFFORT

2.1 Motivations

The congressionally mandated Live Fire Test (LFT) for aircraft in development, passed in 1987, requires realistic vulnerability tests with combustibles on-board and using weapons likely to be encountered in combat. Vulnerability testing of components and subsystems is also strongly encouraged early in the development cycle in order to identify kill modes and eliminate them without major weight and cost penalties [1].

LFT is supposed to be conducted as if the aircraft was in flight, and had been hit by an anti-aircraft artillery round. Typically, it is performed on a wing. The tanks are loaded with fuel, and high-velocity air is blown by a battery of jets across the wing which is loaded by computer-controlled hydraulic jacks to simulate in-flight loads. In one test, an explosive bullet is fired away from the fuel tank. In another test, it is fired inside the fuel tank. The explosive bullet generates a shock wave that travels through the fuel and imparts loads on the wing's skin and internal structure. Consequently, a portion of the wing skin deforms into the air stream then rips off. If the damaged wing remains largely intact, it is currently concluded that the limited structural damage would enable a pilot to fly the airplane home.

Besides being destructive and therefore expensive, the LFT procedure outlined above has two main deficiencies:

- The high-velocity air blown by the jets and the computer-controlled hydraulic jacks applied to the tip of the wing do not reproduce the in-flight loads. In particular, the hydraulic jacks introduce an unrealistic restraint at the tip of the wing whose root is already cantilevered.
- The loading generated by the hydraulic jacks does not allow the structure to properly react when damaged. The total applied loads need to reconfigure in reaction to the wing's change-of-stiffness and change-of-mass.

Furthermore, additional tests are required to assess the remaining flight capability of the damaged wing and its revised flutter envelope, before it can be concluded that a limited structural damage would enable a pilot to fly the airplane home.

To address the above issues, it was proposed to develop and validate a high-fidelity and high-performance numerical simulation technology for predicting the effects of combat damage on the flight and flutter envelopes of military aircraft. It was also proposed to exploit this numerical simulation technology to develop a more realistic asymmetric dynamic load procedure for LFT based on tethers or embedded and programmable piezoelectric actuators, and to obtain important insights into failure mechanisms that are difficult to obtain from testing alone. As pointed out recently in [2] where the authors reported on a related effort recently launched at the Wright-Patterson AFB, the success of such a needed research endeavor hinges on the availability of a reliable computational methodology for the prediction of nonlinear aeroelastic phenomena. During the last five years, the Principal Investigator (PI) and his research group have engaged in a research effort funded by the AFOSR, and leveraged by the results of an earlier effort supported by the NSF, to advance the state-of-the-art of computational fluid dynamics (CFD)-based computational methods for the

solution of realistic nonlinear aeroelastic problems. They have integrated their developed computational algorithms into AERO, a unique CFD-based aeroelastic simulation capability that addresses not only flow nonlinearities, but also structural and coupled fluid-structure nonlinearities. This on-going research program at the University of Colorado recently culminated with the parametric identification of a full F-16 configuration with clean wings using a detailed finite element representation of the structure and inviscid flow computations in all of the subsonic, transonic, and supersonic regimes. This *blind* analysis, which was performed before the flight test that was conducted at the Edwards AFB to provide validation data, produced numerical results that correlate well with the flight test data. It was proposed to expand the range of applications of AERO to the prediction of the consequences of battle damage on the flight and flutter envelopes of fighters, assessment of the impact of several contributors to aircraft survivability, and assistance in the development of new dynamic live-fire ground testing methodologies that may remedy the shortcomings of current static ground-testing techniques.

After one year of performance on the proposed research overviewed above, the Flight Test Center at the Edwards Air Force Base requested an additional emphasis on researching suitable *aeroelastic reduced-order models*, integrating them in the AERO platform, and assessing their potential for speeding up the prediction of the flutter envelopes of modern aircraft fighters.

2.2 The AERO Nonlinear Aeroelastic Simulation Platform

The AERO-F, AERO-S, and MATCHER codes are a suite of software modules developed by the PI and his research group at the University of Colorado to demonstrate the scientific merit and engineering potential of the three-field formulation of fluid-structure interaction problems and associated computational advances for the solution of nonlinear aeroelastic problems. These codes are portable, and run on a large variety of computing platforms ranging from Unix workstations to shared as well as distributed memory massively parallel computers. They define the AERO nonlinear aeroelastic simulation platform.

The three-dimensional AERO-F module models a flow either by the Euler equations, or by the averaged Navier-Stokes equations augmented by the k-ε or the Spalart turbulence model and a wall function [3]. It operates on static and dynamic unstructured meshes. More specifically, it combines a Galerkin centered approximation for the viscous terms, and a Roe upwind scheme for the convective fluxes. Higher-order spatial accuracy is achieved through the use of a multidimensional piecewise linear reconstruction that follows the principle of the Monotonic Upwind Scheme for Conservative Laws [4]. Time-integration on moving grids is carried out by an implicit backward difference scheme that satisfies its Discrete Geometric Conservation Law (DGCL) and achieves second-order accuracy on dynamic meshes [5]. Sensitivity analysis is available and performed by an analytical approach using either the direct [6] or adjoint [7] method. All linearized systems of equations are solved by the Restricted Additive Schwarz preconditioned GMRES iterative algorithm [8].

The AERO-F module supports two robust structure-analogy methods for constructing dynamic meshes. The first one is based on time-dependent torsional springs [9, 10]. The second method is based on the total Lagrangian approach for solving a fictitious nonlinear elasticity problem [11]. Both methods share in common the idea of constructing a fictitious stiffness of each fluid mesh element that increases to infinity when the area or volume of that element decreases to zero. This

prevents all collapsing mechanisms (node-to-node, node-to-edge, and node-to-face) from occurring during the mesh motion. For applications where the structure undergoes large rotations — for example, aircraft maneuvering — the AERO-F modules invoke a corotational scheme to accelerate the update of the mesh motion [12].

The AERO-S suite of structural modules are capable of linear and nonlinear static, sensitivity, vibration (eigen), and transient FE analyses of restrained as well as unrestrained homogeneous and composite structures.

AERO-F and AERO-S are loosely coupled by a state-of-the-art staggered solution procedure that was recently proved to be formally second-order time-accurate and numerically demonstrated to be stable [13]. In this procedure, AERO-F and AERO-S communicate via run-time software channels. They exchange aerodynamic and elastodynamic data across non-matching fluid and structure mesh interfaces using data structures generated by the preprocessor MATCHER [14]. Such exchanges are governed by a provably conservative algorithm for discretizing the transmission conditions at the fluid-structure interface [15].

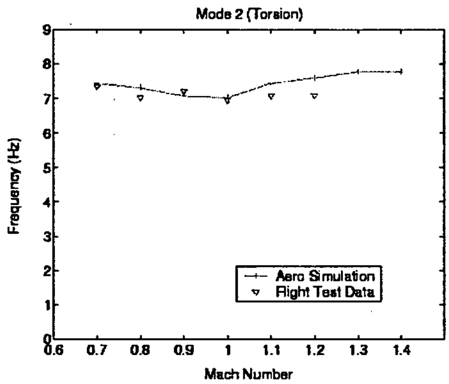
The AERO simulation platform was validated with the inviscid flutter analysis of the AGARD Wing 445.6 [16], and the parametric identification of a full F-16 configuration. For the AGARD Wing 445.6 problem, it proved to be capable of capturing correctly the transonic dip. It demonstrated superior computational efficiency by operating accurately with a fluid time-step Δt_F that is 10 to 22 times larger, and a coupling time-step $\Delta t = \max(\Delta t_S, \Delta t_F)$ that is 20 to 46 times larger than reported in the literature for other CFD-based nonlinear aeroelastic codes [16]. For the F-16 clean wing problem (but with tip missiles), AERO produced aeroelastic results that correlate well with the flight test data generated by the Flight Test Center at the Edwards Air Force Base (see Fig. 1).

2.3 New Research Tasks

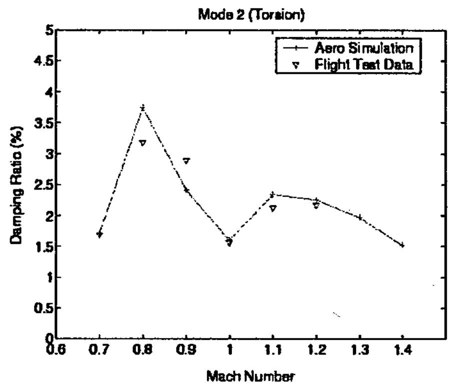
The following five research tasks were originally proposed to meet the objectives stated in Section 1.

2.3.1 The Zero Time-to-Damage and Constant-Damage Assumptions (Research Task 1)

In order to develop an initial understanding of the effect of bullet-induced damage on aircraft performance, it will be assumed that: (a) damage is instantaneously inflicted by the explosive bullet to the aircraft or aircraft wing — that is, the aircraft or aircraft wing changes from an undamaged geometric, stiffness, and mass configuration to a damaged geometric, stiffness, and mass configuration in an infinitely small amount of time, and (b) damage is represented by a *stationary* hole or collection of holes in *both* the computational structural mechanics (CSM) and CFD models. The first assumption was recently proposed in [2] and simplifies modeling and simulation by ignoring the damage formation process. The second assumption reduces the complexity of post-damage simulations as it ignores the effect of damage propagation. Both assumptions are reasonably sound, at least in the context of the initial phase of the proposed research effort as well as the spirit of current live-fire tests. It is also noted that this initial modeling and simulation strategy is an



(a) Torsional frequency



(b) Torsional damping coefficient

Figure 1: Aeroelastic parameters for an F-16 Block 40 at an altitude of 3,000 m

improvement over the strategy recently outlined in [2] because it accounts for the effect of damage not only in the CSM model, but also in the CFD model.

2.3.2 Phantom Structure and Fluid Elements (Research Task 2)

When investigating the worst-case scenario for the location and size of a hole, or performing a sensitivity analysis with respect to these parameters, the amount of preprocessing required by the repetitive CSM and CFD model modifications to account for damage is such that the simulation strategy suggested in Section 2.3.1 becomes very cumbersome. In order to reduce this amount of overhead and automate the process as much as possible, it was proposed to develop and implement the following concept of "phantom" elements in both CSM and CFD technologies.

Here, a phantom element refers to a discretization element which can be conveniently switched "on" or "off" by the analyst in order to enable or disable the effects of damage in a mathematical model, consistently with the assumptions outlined in Section 2.3.1. In a CSM model, any finite element can be designated as a phantom element. By default, the phantom element is switched off and acts like any other element. When switched on, its stiffness and mass properties are automatically set to zero. In a CFD model, phantom elements are located through the thickness of the surface representation of the aircraft, and can share faces with regular elements. By default, a phantom fluid element is switched off and does not exchange any flux with any neighboring element. When switched on, it acts like any other fluid element but accepts a specific initialization of the flow conservative variables at its nodes (see Section 2.3.3).

2.3.3 Transient Intermediate Effects (Research Task 3)

As outlined in Section 2.3.2, after a damage scenario is decided and defined in terms of holes in the aircraft, it can be implemented in both CSM and CFD models by turning on the appropriate subset of the designated phantom elements. For a post-damage simulation, the initialization of the CSM model is straightforward, and that of the CFD model can be performed as follows. First, a steady (or unsteady) flow solution is computed for the time just before damage is inflicted — that is, for the undamaged configuration. Then, the flow conservative variables at the nodes attached to the activated phantom elements are initialized by the free-stream conditions, and the remainder of the flow conservative variables are initialized by the solution of the undamaged flow configuration.

It was also proposed to investigate the intermediate transient effects by the following incremental approach. Rather than applying the full-sized hole in one step, one can apply a series of telescoping holes where the size of the smallest one is limited by the resolutions of the CSM and CFD models, and the largest one is the intended hole. The concept of phantom elements summarized in Section 2.3.2 makes this simulation strategy very convenient and computationally efficient.

2.3.4 Coupled Sensitivity Analysis (Research Task 4)

In order to obtain important insights into failure mechanisms that are difficult to obtain from testing alone, assess the impact of several contributors to aircraft survivability, and enable fast linearized solution methodologies suitable for "what-if" type of simulations, it was also proposed

to perform the coupled fluid-structure sensitivity analysis of flight mechanics and flutter criteria with respect to damage-related parameters, by the adjoint method [17].

2.3.5 Damage-Induced Changes to Flight Mechanics and Aeroelastic Stability (Research Task 5)

Current live-fire tests do not address the damage-induced changes to the flight mechanics and aeroelastic stability of an aircraft. However, its is crucial to determine these changes as they can lead to the abortive impairment of the ability of an aircraft to accomplish its designated mission, or cause its premature failure.

Hence, it was proposed to expand the AERO simulation technology to address the assessment of the remaining flight capability of a damaged aircraft in general, and produce its revised flutter envelope in particular. It was also proposed to apply the resulting simulation technology to improve our understanding of the damage-induced changes to the flight mechanics and aeroelastic stability of an aircraft, and develop some practical and reliable rules of thumb for this problem.

2.3.6 A Realistic Dynamic Loading Methodology (Research Task 6)

The ground-loading techniques that are currently used in live-fire tests do not reproduce the in-flight loads. Furthermore, they do not reconfigure the applied loads in reaction to the wing's change-of-stiffness and change-of-mass. For these reasons, current live-fire tests may fail to provide accurate and complete vulnerability assessments. Hence, it was proposed to investigate a reconfigurable wing loading methodology which has a better potential for replicating the loads encountered during flight. The proposed idea was based on shape control actuation and can be implemented, at least in principle, with embedded piezoelectric actuators, thermal actuators, or even tethers. Unlike hydraulic jacks, embedded piezoelectric and thermal actuators do not restrain the wing at any location, and tethers soften the restraints they induce because of their compliance.

2.3.7 Validation and Technology Transfer (Research Task 7)

Finally, it was also proposed to collaborate with Dr. Greg Czarnecki and his team at the Wright-Patterson AFB to validate the CFD-based simulation technology to be researched and developed, and assess the feasibility of the proposed dynamic loading methodology. It was also proposed to work with Dr. Mike Love at Lockheed-Martin Aeronautics to explore the best approach for integrating and/or transforming the proposed modeling and simulation technology into a vulnerability software tool that can be used for developing vulnerability target models and performing vulnerability analyses to support JSF decisions.

2.3.8 Aeroelastic Reduced-Order Models for Complete Fighter Configurations (Research Task 8)

As mentioned in Section 2.1, after one year of performance on this proposed research grant, the Flight Test Center at the Edwards Air Force Base requested an additional emphasis on aeroelastic

reduced-order models (ROMs) for complete fighter configurations. To address this request, an additional research task was formulated. This task includes researching suitable aeroelastic ROMs, their integration in the AERO simulation platform, and the assessment of their potential for speeding up the prediction of flutter envelopes.

3 TECHNICAL ACHIEVEMENTS

During the first two years of funding, effort focused on Research Task 6 and Research Task 8.

3.1 Outcome of Research Task 6: A Stress-Control-Based Live-Fire Ground Testing Methodology

LFT is supposed to be conducted as if the aircraft was in flight, and had been hit by an anti-aircraft artillery round. Typically, it is performed on a wing. The tanks are loaded with fuel, and high-velocity air is blown by a battery of jets across the wing which is loaded by computer-controlled hydraulic jacks to simulate in-flight loads. In one test, an explosive bullet is fired away from the fuel tank. In another test, it is fired inside the fuel tank. The explosive bullet generates a shock wave that travels through the fuel and imparts loads on the wing's skin and internal structure. Consequently, a portion of the wing skin deforms into the air stream then rips off. If the damaged wing remains largely intact, it is currently concluded that the limited structural damage would enable a pilot to fly the airplane home [18].

The LFT procedure outlined above has at least one main deficiency: the high-velocity air blown by the jets and the computer-controlled hydraulic jacks applied to the tip of the wing do not reproduce the in-flight loads. In particular, the hydraulic jacks introduce an unrealistic restraint at the tip of the wing whose root is already cantilevered.

To reproduce the in-flight loads, a loading methodology should reproduce the true stress state of the structure. Given a set of flight conditions, this stress state can be predicted fairly accurately by numerical aeroelastic simulation. Hence, the main idea reported here is to consider a wing, instrument it with a number of embedded actuators, and program these actuators to produce the desired aeroelastic stress state field denoted here by $\bar{\mathbf{s}}$. Such actuators could be, in principle, piezoelectric actuators, thermal actuators, simple tethers, or any combination of these. Unlike hydraulic jacks, embedded actuators do not restrain the wing at any location, and potential tethers soften the restraints they induce because of their compliance.

Let g_i denote the gain of the i-th embedded actuator, and $\mathbf{u}_i$ denote the displacement field of a wing structure due to this actuator and its gain g_i. Under the usual linear assumption, when all N_a embedded actuators are activated, the total displacement of the wing is

$$\mathbf{u} = \sum_{i=1}^{i=N_a} \mathbf{u}_i g_i = \mathbf{U}\mathbf{g} \tag{1}$$

where $\mathbf{U}$ is the matrix of displacement fields $\mathbf{u}_i$, and $\mathbf{g}$ is the vector of gains g_i. From Eq. (1), it follows that if $\mathbf{s}_i$ denotes the stress field associated with $\mathbf{u}_i$, then the stress state of the wing

structure is given by

$$\mathbf{s} = \sum_{i=1}^{i=N_a} \mathbf{s}_i g_i = \mathbf{S}\mathbf{g}$$

where $\mathbf{S}$ is the matrix of stress fields $\mathbf{s}_i$ associated with the gains g_i.

Hence, the crux of the idea reported here is to find the gain vector for which $\mathbf{s} = \bar{\mathbf{s}}$ — that is,

$$\mathbf{S}\mathbf{g} = \bar{\mathbf{s}}. \tag{2}$$

Unfortunately, Eq. (2) can be exactly satisfied only if the total number of actuators N_a is equal to the number of degrees of freedom of interest, and using such a large number of actuators is unfeasible as well as undesirable. In particular, the component of the structure that is expected to be damaged should not be instrumented so that no actuator is destroyed and the in-flight loads are reproduced as much as possible after damage is inflicted on the instrumented structure. Hence, a residual

$$\mathbf{r} = \bar{\mathbf{s}} - \mathbf{S}\mathbf{g} \tag{3}$$

is to be accepted but minimized. Here, the Euclidean metric is chosen for this purpose. Furthermore, it is well-known that some actuator locations are more efficient than others in prescribing a particular shape [19, 20], and therefore a particular stress state. For this reason, a good strategy consists in minimizing $||\bar{\mathbf{s}} - \mathbf{S}\mathbf{g}||_2$ over both the locations and gains of the N_a actuators, for different values of N_a.

Alternatively, after damage is inflicted on the wing, it can be inspected and described by holes in the computational structural dynamics and computational fluid dynamics models. Then, the vector of actuator gains can be reset to the value which minimizes

$$||\mathbf{r}||_2 = ||\bar{\mathbf{s}}_d - \mathbf{S}\mathbf{g}||_2, \tag{4}$$

where $\bar{\mathbf{s}}_d$ is the stress state predicted for the damaged wing by numerical aeroelastic simulation. Once the damaged wing is loaded according to this reconfigured gain vector, its structural integrity can be assessed, and further numerical simulations can be performed to evaluate its remaining flight capability.

In summary, the stress-control-based live-fire ground testing methodology developed so-far is governed by the mathematical problem

$$\min_{\mathbf{g} \in \mathbb{R}^{N_a}} \quad ||\bar{\mathbf{s}} - \mathbf{S}\mathbf{g}||_2 \tag{5}$$

$$\mathbf{C}(\mathbf{g}) \leq 0, \tag{6}$$

where $\mathbf{C}(\mathbf{g})$ is a matrix of constraints specifying, for example, that each actuated member does not exceed a certain percentage of the yield stress and that the total energy of actuation does not exceed a certain threshold. Note however that the solution of the above minimization problem is adequate for the envisioned application if and only if $\bar{\mathbf{s}} \in R(\mathbf{S})$, and that the range of $\mathbf{S}$, $R(\mathbf{S})$, depends on the number, location, and type of the actuators.

Let $\mathbf{S}_a$ denote the matrix of stress fields $\mathbf{s}_i$ associated with the gains g_i when *all* members of the test structure are actuated. If $\bar{\mathbf{s}} \notin R(\mathbf{S_a})$, this "range check" indicates that, using the chosen

type of actuators, the test article cannot be put in the aeroelastic stress state $\bar{s}$ even if each one of its members is instrumented. In this case, the range check also suggests that additional internal members and/or external members such as tethers are needed to control the stress sate of the test article. Then, if additional members are introduced in the structure for controlling its stress state, stiffness-and-mass checks must then be performed *a posteriori* to ensure that the few additional members have not significantly changed the characteristics of the structure — for example, its eigen modes.

Advances in the methodology outlined above including the use of one-dimensional versus bender actuators, its accuracy, feasibility (no member yielding, minimum and practical energy requirement), and demonstration for the ARW2 wing have been reported in 2004 in the AIAA paper [7] and documented in the attached comprehensive Ph. D. report entitled "A Stress-Control-Based Live-Fire Ground Testing ". Essentially, it was found that at least for the ARW2 wing, tethers are almost always required to reproduce the in-flight loads with sufficient accuracy.

In order to check whether the above result is primarily due to the fact that the ARW2 wing has a large aspect ratio, the proposed loading methodology was next assessed for *delta*-like wings. The smaller aspect ratio of such wings tends to make their structures statically indeterminate, which in turn tends to improve the performance of self-equilibrated one-dimensional actuators. More specifically, two such wings were considered: a high-speed civil transport wing and an F-16 wing in clean configuration. In both cases and for several damage scenarios, it was also found that external tethers cannot be avoided if in-flight loads are to be reproduced accurately. More specifically, it was found that the entire objective of the loading methodology can be achieved using only a few tethers. For example, it was found that for the F-16 wing, eight well-positioned tethers can reproduce in most cases the in-flight stress states of the wing with a global relative error of the order of 10%. On the other hand, it was also found that the current usage of computer-controlled hydraulic jacks at the tip of a wing to simulate in-flight loads typically results in relative errors that exceed the 50% level.

3.2 Outcome of Research Task 8: Reduced-Order Modeling for Real-Time Flutter

In order to enable real-time flutter analysis, we have developed a computational methodology based on adaptive reduced-order modeling (ROM). In this methodology, the structure is represented by a truncated modal set, the fluid by a reduced-order basis obtained by Proper Orthogonal Decomposition (POD) for a given Mach number, and the resulting basis is adapted for variations in the Mach number by interpolation of the subspace angles. We have implemented this computational technology in AERO and applied it to a complete F-16 fighter configuration. We have demonstrated good correlation between full-order simulation results, reduced-order simulation results, and flight test data, and documented this effort in an AIAA paper to appear in 2005. A short version of this paper entitled "Application of the POD-based ROM Method to a Complete F-16 Fighter Configuration: Validation and ROM Adaptation" is also attached to this final report.

4 PUBLICATIONS ACKNOWLEDGING THIS GRANT

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